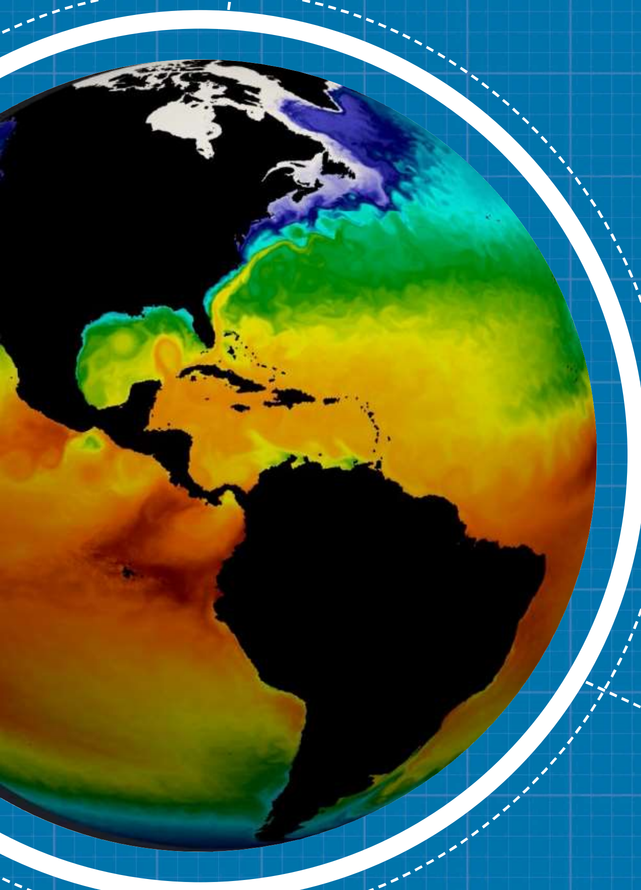

CHAPTER 5

Climate Science

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Contributions of former BERAC member Dr. Katherine Calvin to this work prior to her full-time detail to NASA Headquarters are gratefully acknowledged.

Chapter 5
Key Findings and Recommendations

Key Findings

KF5.1 BER-funded climate science publications are among the most highly cited papers in the field, garnering a higher rate of citations than non-BER publications, particularly for the top 1% and 5% of papers.

KF5.2 BER has demonstrated international leadership in developing and interpreting climate model intercomparisons through the DOE Program for Climate Model Diagnosis and Intercomparison (PCMDI) and was a leading contributor to research earning the 2007 Nobel Peace Prize awarded to the Intergovernmental Panel on Climate Change and former U.S. Vice President Al Gore.

KF5.3 BER is a world leader in climate change and cloud feedback research through its application of the "fingerprint" method to identify signatures of human influence on climate and its development of innovative techniques to quantify cloud feedbacks and pin down equilibrium climate sensitivity.

KF5.4 BER has advanced exascale computing to become one of the world's leading developers of kilometer-scale Earth system models, such as the convection-permitting Energy Exascale Earth System Model.

KF5.5 BER has successfully developed capabilities in crosscutting energy-related research and coupled human-Earth system models, such as the Global Change Analysis Model.

KF5.6 BER leads internationally in capturing ground-based and aerial atmospheric measurements through its Atmospheric Radiation Measurement (ARM) user facility and in advancing physical understanding of atmospheric systems through the associated Atmospheric System Research program.

Recommendations

R5.1 Increase investment in development of kilometer-scale Earth system modeling by advancing exascale computing, artificial intelligence and machine-learning approaches, and model-observation integration.

R5.2 Strengthen international leadership in modeling the coupled human-Earth system by providing more decision-relevant insights and better accounting for model uncertainties.

R5.3 Sustain international leadership in ground-based and aerial measurements and their use in advancing physical process understanding by strengthening collaborations with the satellite community, supporting integration of national and international field-observing systems, and potentially establishing synergistic leadership in laboratory chamber facilities.

R5.4 Strengthen international leadership in model intercomparison activities and in climate sensitivity research by increasing support for PCMDI, the Earth System Grid Federation, and process-oriented exercises that use ARM observations.

R5.5 Establish sustained and substantial funding for expanded collaboration between U.S. agencies and universities to improve research outcomes and integration of efforts to meet societal needs.

R5.6 Create additional means for supporting "blue sky" proposals from DOE scientists to stimulate innovation and workforce engagement.

5 Climate Science

5.1 Overview of BER Climate Science

5.1.1 Atmospheric and Modeling Programs

BER conducts climate science research activities under three programs: the Atmospheric Radiation Measurement (ARM) user facility, the Atmospheric System Research (ASR) program, and the Earth and Environmental Systems Modeling (EESM) program (see Fig. 5.1, this page).

ARM supports well-instrumented ground research sites in the world's most important climate regions and co-located intensive field campaigns at appropriately short physical and temporal scales (arm.gov/about/history). Over the past 30 years, ARM has provided a growing suite of continuous measurements of surface radiative flux quantities, atmospheric state, trace gases, atmospheric aerosols, clouds, and precipitation. Field campaigns are supported at fixed and mobile surface sites via ARM mobile and aerial facility deployments and funding for domestic and international participants.

ASR supports the use of ARM observations and ancillary activities to advance process-level understanding of the key interactions among aerosols, clouds, precipitation, radiation, dynamics, and thermodynamics, with the ultimate goal of reducing the uncertainty in global and regional climate simulations and projections (asr.science.energy.gov). ASR activities are tightly coupled to ARM observations to advance understanding of atmospheric processes using a hierarchy of modeling scales ranging from box models to Earth system models (ESMs).

EESM seeks to simulate and understand DOE-relevant predictability of the Earth system (climatemodeling.science.energy.gov) through three program areas: Earth System Model Development, Regional and Global Model Analysis, and MultiSector Dynamics.

Fig. 5.1. BER Engages in Crosscutting Climate Research. Efforts in atmospheric sciences research, environmental system science, Earth system modeling, and data management incorporate the activities shown in the figure and are supported by various user facilities. Such cross-disciplinary approaches result in, for example, the high-resolution Energy Exascale Earth System Model (E3SM), which can simulate changes in water vapor (tan) and sea surface temperatures (red to blue) as a hurricane moves across the Atlantic Ocean toward the U.S. East Coast. The resulting cold wake affects subsequent intensification of the next hurricane. [Modeling visualization courtesy Los Alamos National Laboratory.]

Within the Earth System Model Development program area, EESM funds development, use, and analysis of the Energy Exascale Earth System Model (E3SM). E3SM is a fully coupled ESM with low-resolution (~100 km), regionally refined (25 km to 100 km), and high-resolution (~3 km) versions (e3sm.org). E3SM's core simulation campaigns focus on answering science questions related to the water cycle, biogeochemistry, and the cryosphere. Through the Regional and Global Model Analysis program area, EESM supports studies diagnosing and analyzing (1) state-of-the-science coupled climate models and ESMs; (2) climate sensitivity and feedbacks from various processes; (3) attribution and detection of climate change and climate variability; and (4) impacts of extreme events, especially droughts, floods, and tropical cyclones. Finally, within the MultiSector Dynamics program area, EESM analyzes interactions between human and natural systems and funds development of the Global Change Analysis Model (globalchange.umd.edu/gcam).

5.1.2 Leadership Assessment

This chapter goes beyond standard metrics, such as publication and citation numbers, to assess BER's international leadership role in the following areas: international committees, Intergovernmental Panel on Climate Change (IPCC) assessment reports, workshop and conference organization, and cutting-edge research and observations.

One indicator of international leadership by BER climate scientists is their participation in committees and working groups of the World Climate Research Programme (WCRP), a premier international organization prioritizing and coordinating climate science research around the world. WCRP engages climate scientists as volunteer coordinators and facilitators of international climate research to develop, share, and apply the climate knowledge that contributes to societal well-being (wcrp-climate.org). BER-funded scientists have consistently demonstrated leadership in committees and working groups for several of WCRP's six core projects (wcrp-climate.org/learn-core-projects), including the Coupled Model Intercomparison Project (CMIP), the Cloud Feedback Model Intercomparison Project, and the Global Energy and Water Exchanges Project. BER scientists have also participated in WCRP Grand Challenges (wcrp-climate.org/component/content/category/26-grand-challenges) and Lighthouse Activities (wcrp-climate.org/lha-overview).

Participation in WCRP enables BER-supported scientists to lead climate research that defines and addresses questions too large or complex to be tackled by a single nation, agency, or scientific discipline. These scientists can influence the international climate science research agenda through international coordination and partnerships and exchange information with BER program managers about compelling WCRP-relevant science questions. These questions may then be reflected in BER-funded research to advance understanding of the multiscale dynamic interactions between natural and social systems affecting climate. BER-supported researchers are widely distributed throughout the WCRP structure, with notable concentrations in the BER climate science focus areas, and thus play key international leadership roles in climate science.

Another indicator of international leadership is participation in the IPCC assessment process as contributors, lead authors, or coordinating lead authors of reports that assess human knowledge of climate change and variability. BER-supported scientists have participated in the IPCC assessment process and all six assessment reports. As contributors, they ensure that the IPCC properly evaluates DOE-funded research results. IPCC reports also regularly cite BER-supported research.

Finally, BER climate scientists lead in organizing international conferences, including serving on organizing committees and leading sessions at major climate science meetings organized by both professional societies (e.g., the American Geophysical Union and the American Meteorological Society) and BER-funded projects (e.g., ARM, Global Change Analysis Model, and AmeriFlux).

5.2 Leadership Status

Publication metrics provide a general overview of how BER-funded climate science compares to the rest of the world. Although BER-funded climate science papers represent only 1.8% of all climate publications between 2010 and 2020, they are cited more often than other publications, accounting for 4.2% of the top 5% most cited publications and 5.4% of the top 1% (see Table 5.1, p. 67). BER climate publications also garner more citations than non-BER publications, with an average 8 citations per publication per year compared to 6.1 for domestic and 3.9 for nondomestic publications. See Appendix C: Approach to Metrics and Methodologies, p. 151, for more details on publication metrics.

Table 5.1 BER Proportion of Climate Science Publications					
Year	**BER % All Pubs**	**BER Top 1%**	**BER Top 5%**	**BER Top 10%**	**BER Top 20%**
2010	1.36%	3.49%	2.10%	2.68%	1.86%
2011	1.61%	7.45%	3.97%	3.18%	2.87%
2012	1.62%	7.69%	4.43%	4.14%	3.46%
2013	2.07%	10.08%	7.65%	5.56%	4.19%
2014	2.08%	3.23%	3.88%	4.33%	3.38%
2015	2.03%	2.99%	4.03%	3.94%	3.87%
2016	2.19%	8.39%	5.59%	4.52%	3.81%
2017	1.75%	3.29%	4.50%	3.59%	2.81%
2018	1.99%	3.59%	4.47%	3.54%	3.53%
2019	1.67%	6.18%	3.05%	2.75%	2.56%
2020	1.59%	2.99%	2.59%	2.87%	2.72%
Avg.	1.81%	5.40%	4.21%	3.74%	3.19%

BER-funded publications are disproportionately represented among highly cited climate science publications. Comparison groups are BER versus all other domestic and nondomestic publications. Top document categories are based on percentile distribution of publications by citation volume. [Courtesy DOE Office of Scientific and Technical Information]

The next six subsections evaluate BER performance based on information gathered from interviews with throught leaders and responses to a Request For Information in the specific areas of climate science that BER funds: ARM and ASR, Earth system modeling, human-Earth system modeling, model intercomparisons, cloud feedback and climate analysis, and enabling capabilities.

5.2.1 ARM and ASR

Nearly all interviewed respondents view ARM as a world leader in ground-based and aerial climate measurements, particularly in supporting field campaigns that bring additional instruments to its fixed and mobile sites (see Fig. 5.2, p. 68). ARM leads ground-based programs around the world in terms of combined data record length and breadth of measurement suites at fixed and mobile sites, diversity of conditions and locations monitored in climate-relevant areas, and influence in studying the climate system. ARM is also world-leading in data management, provision, and exploration, setting the standard for other climate-observing facilities internationally. ARM's lengthy data record is a particular asset for complex multidimensional statistical and trend analysis.

Respondents describe ASR as world leading in understanding atmospheric processes through its use of ARM process-oriented observations. Specifically, ASR leads in boundary layer and troposphere processes, aerosol and cloud microphysical processes, and aerosol-cloud interactions.

Together, ARM and ASR lead in connecting user facility data to global and regional model developments by promoting a hierarchical framework of process modeling that includes the single-column model, cloud-resolving model, large-eddy simulation models, and the Cloud-Associated Parameterizations Testbed (pcmdi.llnl.gov/projects/capt). This framework develops and tests atmospheric physical parameterizations and bridges the scale gap between ARM data and models. ARM and ASR scientists have led or co-led a growing number of process model intercomparison studies conducted by international modeling

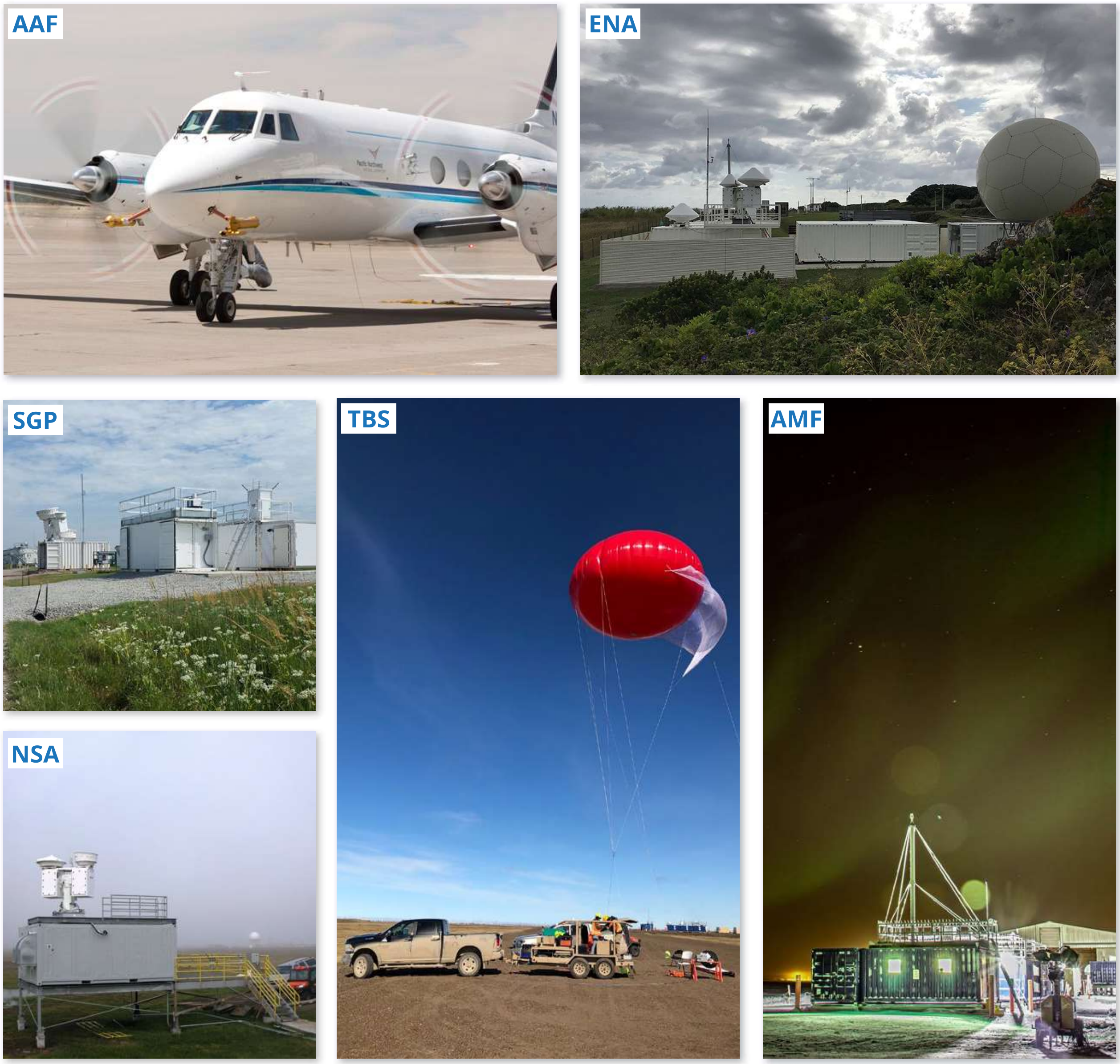

Fig. 5.2. BER Supports Worldwide Deployment of Atmospheric Monitoring Instrumentation. The Atmospheric Radiation Measurement (ARM) user facility provides comprehensive measurements for studying atmospheric processes in areas where they are most needed by the science community. Data are collected by the ARM Aerial Facility (AAF); ARM Mobile Facilities (AMF); tethered balloon systems (TBS); and three fixed atmospheric observatories in the Eastern North Atlantic (ENA), North Slope of Alaska (NSA), and Southern Great Plains (SGP). [All images courtesy ARM]

communities, including the Global Atmospheric System Studies Panel and the preceding Cloud System Study panel of the WCRP Global Energy and Water Exchanges Project. ARM's variational analysis forcing data (arm.gov/capabilities/vaps/varanal) has provided arguably the most widely used forcing data to support process modeling studies worldwide. The ARM Best Estimate data product (arm.gov/capabilities/vaps/armbe) has set a standard for creating climate model–friendly integrated data products for other observational programs or field campaigns such as the Multidisciplinary drifting Observatory for the Study of Arctic Climate (MOSAiC) expedition (mosiaic-expedition.org).

Respondents noted a few areas that could be strengthened:

- While ARM excels at collecting climate and cloud measurements and BER programs support strong modeling efforts, ARM and ASR could increase involvement in laboratory studies as a third pillar of progress in the field. For example, DOE does not have any major aerosol and cloud chamber user facilities, which are now playing a leading role internationally in advancing understanding of aerosol and cloud microphysical processes. Accurately representing these processes is a major challenge of BER's climate model parameterizations.
- ARM field campaign data receive widespread use, but long-term data from ARM's fixed sites lack such a broad user community.
- Limited spatial coverage is another challenge for ARM, which may cause issues with physical parameterizations based on data collected at the limited number of ARM sites.
- Collaboration with the satellite community needs to be strengthened and could be achieved through stronger interagency partnerships at the national level under joint management (see Ch. 7: Integrative Science, p. 103).
- As the international community begins catching up to BER in some areas, such as well-calibrated long-term surface site network measurements, ARM should embrace the expanding community and seek to contribute new leadership roles, such as helping guide integration of U.S. and international climate-observing systems.
- ARM might benefit from leading or co-authoring a strategic plan to address the continuing interagency and international challenge of transferring knowledge from observations to global climate models in a more integrative way.

5.2.2 Earth System Modeling

With its recent development of E3SM, BER now leads convection-permitting climate modeling at the national level. E3SM is one of several Earth system models undergoing independent development in the United States today, along with publicly available models supported by the National Science Foundation (NSF), the National Oceanic and Atmospheric Administration (NOAA), and NASA. BER has demonstrated growing capabilities in Earth system modeling, with E3SM, and in coupling atmospheric, ocean, cryosphere, and land models. Some respondents were impressed with E3SM biogeochemistry modeling and viewed BER as a leader in regional and global model developments. Other respondents pointed to BER's E3SM performance in some areas as evidence that it will take time for the relatively new model to catch up with other world leaders in climate modeling such as NSF's National Center for Atmospheric Research (NCAR) and NOAA's Geophysical Fluid Dynamics Laboratory (GFDL). One respondent noted that the current E3SM lags in the area of chemistry, partly due to the high computational cost required to include complex atmospheric chemistry in the model. Another respondent perceived a major weakness in ocean circulation and ocean biogeochemistry in E3SM. Respondents also saw clear opportunities where BER could take a new leadership role, such as in biological aerosol modeling.

Respondents generally shared the concern that separating E3SM from the NCAR Community Earth System Model (CESM) might create unnecessary duplication of efforts and bifurcate the science community, even though E3SM enables BER to better address DOE's scientific objectives and connect its ESM development to other DOE-funded efforts. Areas needing growth include predictive skill, coupling of processes, and connection to DOE research in energy and human systems. One respondent suggested that DOE allocate resources toward efforts it already leads, such as computing and very high-resolution modeling, rather than using resources to catch E3SM up to groups with standard resolution versions (e.g., 1 degree down to ¼ degree).

Several respondents questioned why E3SM did not play a more prominent role in CMIP Phase 6

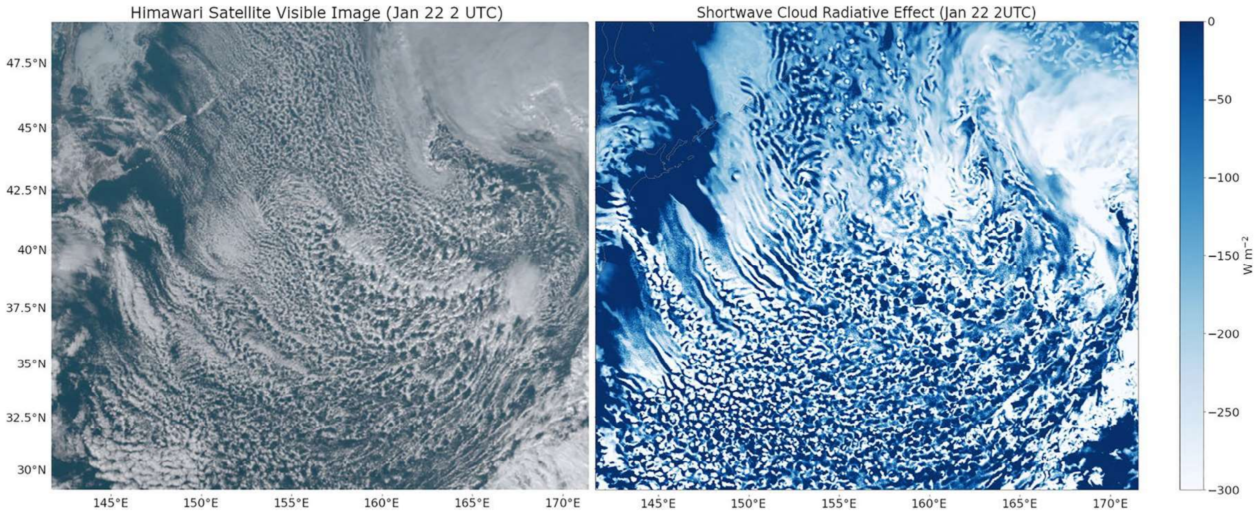

Fig. 5.3. BER Leads in Kilometer-Scale Physical Climate Modeling. Cold-air outbreak off Siberia on January 22, 2020, from a Himawari visible satellite image (left) and a snapshot of shortwave cloud radiative effect from the Simple Cloud-Resolving E3SM Atmosphere Model (SCREAM; right). A comparison of the images reveals striking similarity between observed and simulated cloud structures, suggesting that SCREAM's combination of resolution and boundary layer and cloud parameterizations contains the physics necessary to capture cloud transitions in cold-air outbreaks. [Reprinted under a Creative Commons Attribution 4.0 International License (CC By 4.0) from Caldwell, P. M., et al. 2021. "Convection-Permitting Simulations with the E3SM Global Atmosphere Model," *Journal of Advances in Modeling Earth Systems* **13**(11), e2021MS002544.]

(CMIP6), potentially ceding international leadership, credibility, and prominence in Earth system modeling to other countries. However, another respondent supported the decision and urged E3SM scientists to focus instead on model development of kilometer-scale ESMs. One respondent also noted that the most ambitious kilometer-scale digital twin efforts in Europe will not participate in CMIP because their emphasis on data assimilation and shorter time frames is currently incompatible with CMIP.

Despite some mixed opinions, respondents agree that BER leads or has the potential to lead high-resolution climate modeling with its next generation of high-performance computing facilities. BER's current efforts to develop the global convection-permitting Simple Cloud-Resolving E3SM Atmosphere Model (SCREAM, e3sm.org/the-e3sm-nonhydrostatic-dynamical-core, see Fig. 5.3, this page) position DOE as an upcoming global leader in kilometer-scale physical climate modeling, with competition from only a few currently existing efforts [e.g., the Nonhydrostatic ICosahedral Atmospheric Model (NICAM) in Japan and the Icosahedral Nonhydrostatic Weather and Climate Model (ICON) in Germany]. Respondents commended BER's high-resolution modeling efforts and advocated continued pursuit, ideally in constructive collaboration with the wider U.S. climate modeling community.

An asset for DOE is that kilometer-scale modeling resolutions match kilometer-scale observations from satellite instruments, but the most internationally competitive high-resolution modeling may have moved toward digital twin efforts, which require data assimilation. Such work in Europe is accompanied by major investments to partner and exchange information with public and private stakeholders, as discussed further in Ch. 7: Integrative Science (see p. 103). One respondent noted a need to balance BER's high-resolution modeling efforts with its continuing improvements to the low-resolution E3SM; this would address BER's mission-driven questions related to coupled human-Earth system interactions and prognostic prediction of sea-level rise. For this work, E3SM requires a state-of-the-art, low-resolution model with major biases fixed because very

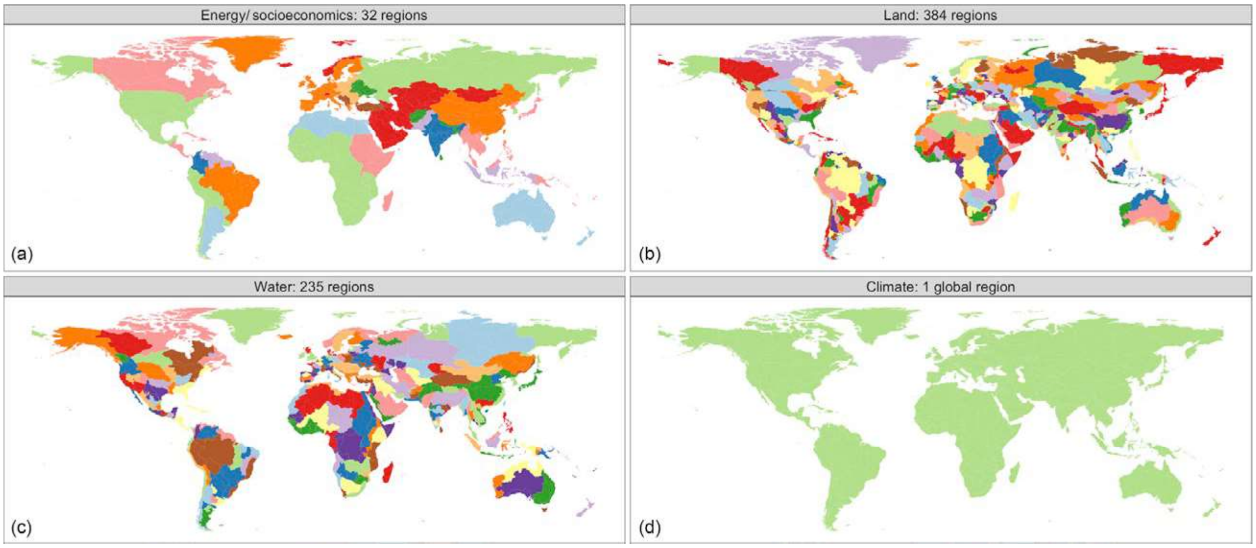

Fig. 5.4. Modeling Coupled Human-Earth Systems. The Global Change Analysis Model (GCAM) represents five different interacting and interconnected systems: energy, socioeconomics, land, water, and climate. The economic and energy systems are represented by 32 geopolitical regions **(a)**, providing insights about broad international socioeconomic and energy dynamics. The land system is based on a combination of geopolitical boundaries and water basins, resulting in 384 regions **(b)**. The water system is subdivided into 235 regions based on water basins **(c)**. Climate is considered a single global region **(d)**. [Reprinted under a Creative Commons 4.0 International License (CC BY 4.0) from Calvin, K., et al. 2019. "GCAM v5.1: Representing the Linkages Between Energy, Water, Land, Climate, and Economic Systems," *Geoscientific Model Development* **12**. 677–698.]

high-resolution climate models would require too much computing power for hundreds of years of simulations to generate various future emissions scenarios.

Some respondents noted that BER effectively directs its funded research around model uncertainty, promotes process understanding using observations, and encourages close collaborations between DOE national laboratories and research institutions. Others encouraged BER to further connect modeling and observational communities, as well as communities developing machine-learning approaches and new tools. BER could benefit from a strategic plan that comprehensively extends beyond BER modeling to interface with the U.S. and international ESM community.

5.2.3 Human-Earth System Modeling

Traditionally, human influence over the Earth system and Earth's influence over human systems have been studied separately. However, neglecting the interactions between human and Earth systems can miss important emerging properties, bias projections, and misinform projection-based decisions (Reed et al. 2022). For example, decisions involved in designing a reliable and cost-effective electricity distribution system in a coastal region are influenced by projections of Earth system components (e.g., storm surges), human system components (e.g., population changes), and their interactions (e.g., changes in migration and infrastructure hardening in response to realized and projected hazards; Reed et al. 2022).

BER-supported climate research provides opportunities to improve the analyses and projections of coupled human-Earth systems and their interactions in addition to the physical and biogeochemical systems traditionally included in climate research. Examples of BER-supported human-Earth system research include the development of human system models, the coupling of human system models to ESMs, and the incorporation of human and managed systems within ESMs.

BER has supported innovative research on coupled human-Earth systems with world-renowned researchers and tools. For example, the Global Change Analysis Model (Calvin et al. 2019; see Fig. 5.4, this page) has been used to produce scenarios that provided crucial inputs to the IPCC assessment process (Moss et al. 2010). Another example is the recently established MultiSector Dynamics community of practice, a multidisciplinary collective of university and national laboratory researchers working at the interface of human and natural systems (multisectordynamics.org). BER has the potential to become an international leader in the unique and vital MultiSector Dynamics research area and provide decision-relevant insights by considering model uncertainties. Historically, BER-supported researchers contributed to building and sustaining MultiSector Dynamics and linking it to other fields, but the international presence of these researchers has waned in recent years even though this research area is crucial to determining future international leadership.

Respondents identified several potential opportunities to strengthen human-Earth system modeling:

- Develop strategies to improve predictive understanding of coupled human-Earth systems that include relevant uncertainties and thereby better inform decision-making.
- Recruit personnel representing an expanded range of disciplines (e.g., determine how to attract and retain social scientists beyond the discipline of economics).
- Improve linkages between BER-supported U.S. activities and the international community.

5.2.4 Model Intercomparisons

BER is an international leader in climate model intercomparisons, supporting numerous activities including CMIP, which is arguably the most influential and high-profile model intercomparison activity devised to date (see Case Study: CMIP—Coupled Model Intercomparison Project, p. 73). BER's leadership in this area began in the late 1980s with the first climate model intercomparison, the Atmospheric Model Intercomparison Project (AMIP). Formulated under the auspices of the WCRP, AMIP was run by Larry Gates, the director of the BER-supported Program for Climate Model Diagnosis and Intercomparison (PCMDI) at Lawrence Livermore National Laboratory. Through WCRP, PCMDI organized modeling centers around the world to perform AMIP simulations, which were atmospheric models forced by time-evolving observed sea surface temperatures. PCMDI then collected model outputs and made the data available for analysis by scientists around the world. BER's involvement helped extend climate model intercomparison beyond the United States to lead the world's climate scientists in understanding common behaviors and errors in atmospheric models. This work set a precedent for future decades of ongoing BER leadership in international climate model intercomparisons.

While AMIP compared atmospheric components of climate models, CMIP was formulated to compare global coupled climate models with components of atmosphere, ocean, land, and sea ice. CMIP was established with BER leadership provided by PCMDI and BER-supported scientists in WCRP. It has now evolved, with contributed DOE leadership at various levels, to become the pre-eminent international climate model intercomparison activity and the gold standard of model intercomparisons due to its methodology, infrastructure, and representation of international state-of-the-art climate modeling capabilities.

To facilitate sharing of CMIP output and other data, BER supports the Earth System Grid Federation (ESGF), which provides the climate modeling community with distributed data archiving and access capabilities that replace data sharing formerly achieved by shipping data tapes to PCMDI. BER also continues to support model and data evaluation through the PCMDI Metrics Package (PMP) and the Coordinated Model Evaluation Capabilities metrics package. This package includes PMP, the International Land Model Benchmarking (ILAMB) project, and other interagency evaluation packages, thereby enabling comprehensive and holistic evaluations of ESMs.

The model intercomparison landscape is changing as more modeling groups and climate scientists around the world perform intercomparisons not only under the CMIP umbrella but also in stand-alone intercomparisons led by individual research communities.

Continued on p. 75

CASE STUDY

CMIP—Coupled Model Intercomparison Project

The Coupled Model Intercomparison Project (CMIP) is the most prominent and significant international model intercomparison project devised to date. It has achieved far-reaching success in the international climate science community thanks to support and leadership from BER.

Global climate models that realistically couple atmospheric components with ocean, land, and sea ice components first began to emerge in the 1980s. In 1989, climate scientist Larry Gates established and became the first director of the BER-supported Program for Climate Model Diagnosis and Intercomparison (PCMDI) at Lawrence Livermore National Laboratory to help standardize the field of climate modeling. As a pioneer in his field, Gates was selected to chair a World Climate Research Programme (WCRP) committee that formed a panel to run the new CMIP endeavor. Two BER-supported scientists were among the five members of the first CMIP Panel, and the panel organized the first international workshop on global coupled climate modeling in 1994. The outcome of the workshop was the first phase of CMIP (CMIP1) in 1995 and the second phase, CMIP2, in 1997.

PCMDI established an early international leadership role in CMIP by collecting model outputs from modeling centers and making those data available for analysis by scientists around the world. It also analyzed multimodel datasets and formulated new metrics to evaluate model simulations. Scientific papers emerging from these analyses by DOE-supported scientists and others internationally underpinned key elements of the 2001 Intergovernmental Panel on Climate Change (IPCC) Third Assessment Report.

With continued BER leadership, CMIP3 took model intercomparison to the next level beginning in 2003 with an unprecedented set of coordinated climate change experiments performed by 16 modeling groups from 11 countries using 23 models. PCMDI archived an astounding 31 terabytes of model data made freely available to the international scientific community. Data were accessed via the Internet by more than 1,200 scientists who produced hundreds of scientific papers. The CMIP3 multimodel dataset and associated papers comprised the foundational elements of the 2007 IPCC Fourth Assessment Report and contributed to the awarding of the 2007 Nobel Peace Prize to IPCC science teams.

Takeaway

BER support of and leadership in CMIP has been vital to the project's far-reaching success in the international climate science community.

CMIP5, approved by the WCRP Working Group on Coupled Modelling (WGCM) in 2008, became the most comprehensive model intercomparison effort yet attempted. It had become clear during CMIP3 that climate change science was undergoing a profound paradigm shift. Scientists were pursuing (1) initialized decadal predictions to study near-term climate change; (2) first-generation Earth system models with a coupled carbon cycle to study long-term feedbacks past mid-century with new mitigation scenarios; and (3) new tangible linkages throughout the climate science community including biogeochemistry, atmospheric chemistry, land surface, climate change impacts, and integrated assessment modeling. Through PCMDI, BER structured distributed access of CMIP model data by designing and formulating the Earth System Grid, which enabled modeling centers to upload their data to publicly accessible servers rather than sending their data to PCMDI. With essential funding from BER, the Earth System Grid ultimately joined international partners to become the Earth System Grid Federation (ESGF), an impressive international effort enabling scientists from around the world to more readily download model data. The hundreds of papers resulting from greater access to this data comprised a central part of the 2013 IPCC Fifth Assessment Report.

In 2013, BER led initial planning for CMIP6, which now included 33 modeling groups from 16 countries and

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CASE STUDY

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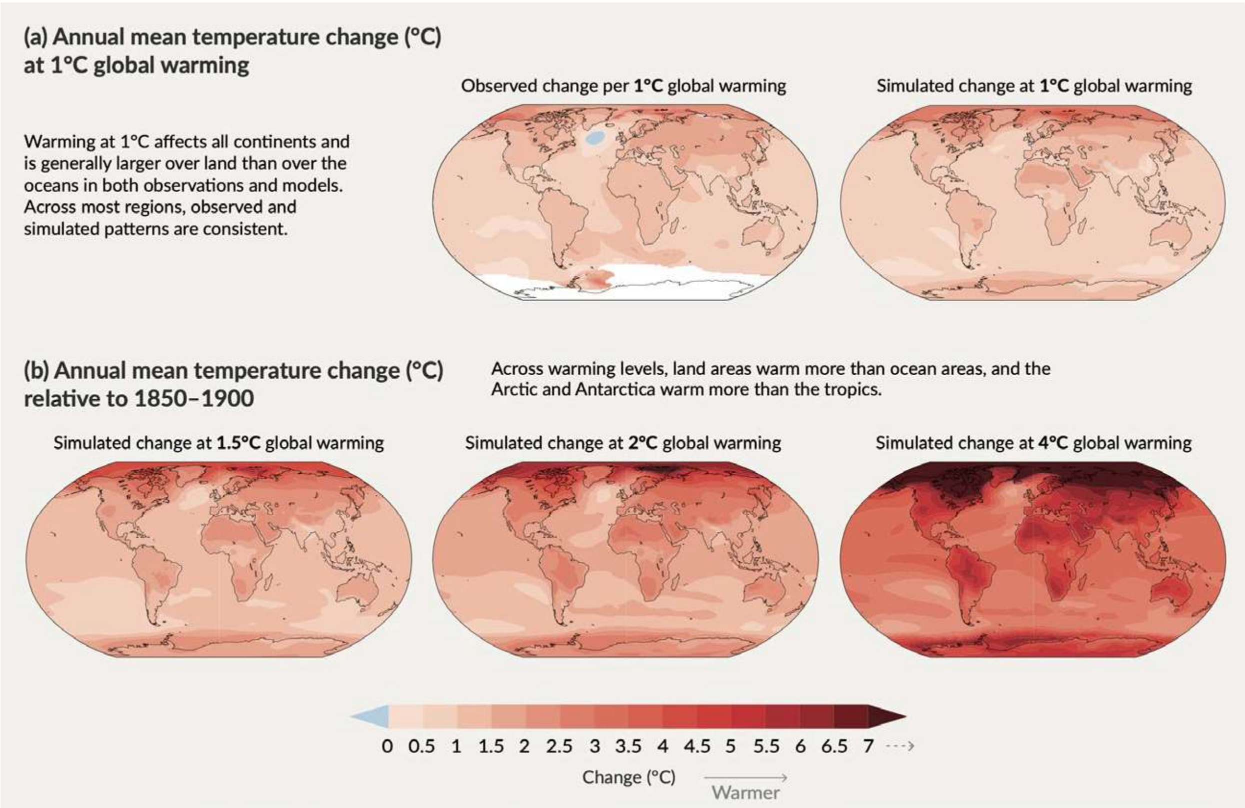
required more formal arrangements for international infrastructure. BER scientists led the WGCM Infrastructure Panel to set standards and policies for sharing climate model output, including establishing input datasets for model intercomparison projects (input4MIPs, esgf-node.llnl.gov/projects/input4mips) to provide boundary conditions and forcing datasets for CMIP6. DOE also provided crucial support for ESGF, the federated data archive hosting CMIP6 data. Model data submitted via ESGF was routinely evaluated using two metrics packages: the DOE-supported PCMDI Metrics Package and the European-based Earth System Model Evaluation Tool.

Similar to previous CMIP phases, thousands of scientists around the world, including DOE-supported scientists at PCMDI and elsewhere, published analyses of CMIP6 model data, which comprised a central element of the 2021 IPCC Sixth Assessment Report (see figure, this page). As with previous IPCC reports, the sixth assessment of future climate change would not have been possible without key leadership from BER-supported scientists in the WCRP-organized CMIP6 model intercomparison activity, an effort that included contributions from modeling groups around the world.



Recent and Future Warming from CMIP6 Models. A key figure from the Intergovernmental Panel on Climate Change *Sixth Assessment Report Summary for Policymakers* shows that changes in regional mean temperature, precipitation, and soil moisture grow larger with each increment of global warming. [Figure SPM.5 from IPCC 2021: Summary for Policymakers. In: *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change.* Masson-Delmotte, V., et al. (eds.). Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 3–32.]

Continued from p. 72

CMIP itself has matured to the point that WCRP established a CMIP Project Office in the United Kingdom to handle CMIP logistics. The Project Office also tracks the growing range of non-CMIP intercomparisons now taking place.

BER and international scientists are broadly engaged in considerable discussion regarding what form CMIP Phase 7 should take, if any. A couple of respondents questioned whether BER should continue to participate in and support CMIP. It is expected that BER will continue to support international model intercomparisons whatever form they ultimately take—by funding either individual scientists or national laboratory groups—because of the significant advancements the work has enabled. CMIP has moved the climate science community firmly into the era of multimodel analyses, and modeling groups gain international visibility and credibility by contributing to comprehensive state-of-the-art datasets. Moreover, analyses of CMIP model data have produced hundreds of scientific papers and advanced the science in ways that complement and provide insights into single-model analyses.

However, separate communities will also likely begin running their own model intercomparisons rather than incorporate their intercomparison activities into the CMIP effort. If this occurs, the model intercomparison effort will become more distributed, but BER can continue its leadership role through PCMDI by tracking intercomparison activities taking place in different communities. BER can also work through WCRP and the CMIP Project Office to participate in and support intercomparison efforts. Certain traditional CMIP simulations may become more operationalized (i.e., simulating historical and future climate change scenarios), but model intercomparisons to study distinct processes and mechanisms in focused disciplinary research communities may achieve greater prevalence scientifically.

Respondents generally concluded that BER-supported scientists should continue to lead international intercomparison activities, including future CMIP phases, as well as intercomparisons organized by individual constituent research communities.

5.2.5 Cloud Feedback and Climate Analysis

BER leads in cloud feedback and climate sensitivity research internationally, as noted by several respondents and as indicated by WCRP reports and IPCC assessment reports on climate sensitivity. Major breakthroughs by BER-supported scientists include understanding cloud feedbacks by decomposing the overall feedback into tangible mechanisms testable by observations (see Case Study: Cloud Feedbacks and Climate Sensitivity, p. 76). BER scientists further developed the concept of emergent constraints to assess aspects of climate feedbacks using observational metrics. The international research community now widely uses the "cloud radiative kernel" technique for quantifying and decomposing cloud feedbacks. BER scientists also pioneered the development and application of instrument simulators to improve comparisons between clouds simulated by climate models and satellite observations.

BER also leads in climate change detection and attribution. BER climate scientists drew from the work of Klaus Hasselmann, a climate modeler and recipient of the 2021 Nobel Prize in Physics, by applying a "fingerprint" method he developed to detect human influence on surface, atmospheric, and ocean temperatures and on different components of the hydroclimate. Their work contributed significantly to advancing the fingerprint research. Continued support for cloud feedback and climate sensitivity research will enable BER to maintain its leadership position in these areas.

5.2.6 Enabling Capabilities

BER climate science includes research and development of enabling capabilities and technologies that support climate research. Enabling capabilities include next-generation computing, artificial intelligence and machine learning (AI/ML), and data assimilation. DOE leads in the development of climate model codes for next-generation computers in the United States,

Continued on p. 78

CASE STUDY

Cloud Feedbacks and Climate Sensitivity

BER-funded scientists have driven major efforts to understand how clouds affect Earth's energy budget, how and why cloud properties respond to climate change, and how sensitive Earth is to carbon dioxide. These accomplishments, outlined below, have advanced international efforts to constrain climate models and quantify Earth's equilibrium climate sensitivity (ECS).

Takeaway

BER is a world leader in understanding how clouds affect Earth's energy budget, how and why their properties shift under climate change, and how sensitive Earth is to carbon dioxide.

Novel Techniques Developed for Quantifying Cloud Feedbacks and Revealing Underlying Causes

One example is the "cloud radiative kernel" technique used to quantify the sensitivity of top-of-atmosphere radiative fluxes to cloud fraction perturbations and decomposing cloud feedbacks into different cloud types (Zelinka et al. 2012a,b; 2013). This method quickly gained attention in the climate science community and has been cited over 600 times (Google Scholar 2/21/2022). Results from these papers featured prominently in "Chapter 7: Clouds and Aerosols" of the Intergovernmental Panel on Climate Change (IPCC) working group report "AR5 Climate Change 2013: The Physical Science Basis" (Boucher et al. 2013). In partial recognition of this work, DOE atmospheric scientist Mark Zelinka of Lawrence Livermore National Laboratory received the 2022 American Meteorological Society's Henry G. Houghton Award for "innovative advances in understanding the critical involvement of clouds to achieve a better understanding of climate interactions."

Cloud Feedbacks Decomposed into Tangible Mechanisms Testable by Observations

This breakthrough in understanding cloud feedbacks was achieved using so-called "emergent constraints" (Klein and Hall 2015). Emergent constraints are physically explainable empirical relationships between characteristics of the current climate and the long-term climate prediction that emerge in collections of climate model simulations (Klein and Hall 2015). Confirmed emergent constraints identify the areas of a model's simulation of the current climate that are most important for future climate predictions, and they suggest potentially observable predictors that might constrain model predictions. BER scientists recently used this approach to estimate observationally constrained near-global marine low cloud feedback, finding that it is positive but not as large or uncertain as previous estimates (Myers et al. 2021).

Emergent Constraints Applied to Assess Aspects of Climate Feedbacks Using Observational Metrics

DOE scientists Stephen Klein and Mark Zelinka led a recent review article for the World Climate Research Programme (WCRP) assessing the science surrounding how much the Earth will warm in response to a doubling of carbon dioxide (Sherwood et al. 2020). The two led an international group in assessing process evidence from satellite observations, global climate models, large-eddy simulations, and theory to produce a new estimate of Earth's climate sensitivity. The estimate, when combined with estimates from historical warming since the late 1800s and paleoclimate, narrowed the range of Earth's equilibrium climate sensitivity from the often-quoted range of 1.5 to 4.5 kelvins to a likely range of 2.6 to 3.9 kelvins (see figure, p. 77). The researchers' progress on this longstanding issue earned the article runner-up for Science Magazine's 2020 Breakthrough of the Year, as reported in the brief article "Global Warming Forecasts Sharpen" (Voosen 2020). The new analysis provides a better constraint for climate models and served as a key input for the climate sensitivity portion of the IPCC Sixth Assessment Report.

Continued on next page

CASE STUDY

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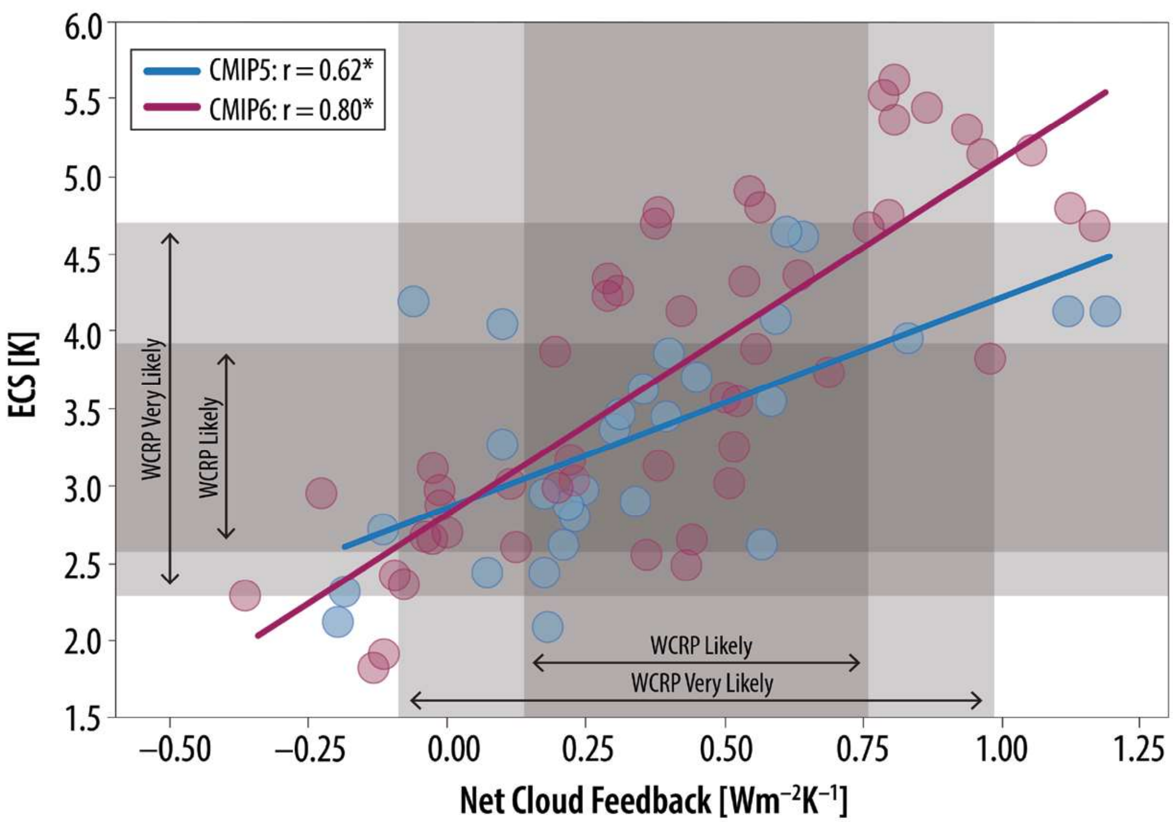
Increased Climate Sensitivity Predicted by Newest Earth System Models

A recent study led by BER scientists determined that the latest generation of global climate models used in the Coupled Model Intercomparison Project predicted greater warming in response to increasing carbon dioxide than previous models (Zelinka et al. 2020). The researchers pointed to changes in how clouds responded to temperature shifts as the primary cause. Specifically, the newer models predicted a greater decline in water content and areal coverage of low-level clouds with greenhouse warming, causing enhanced planetary absorption of sunlight. This important finding was featured in a research spotlight in the science news magazine *Eos* (Shultz 2020). The work was also prominently featured in "Chapter 7: The Earth's Energy Budget, Climate Feedbacks, and Climate Sensitivity" in the IPCC working group report "AR6 Climate Change 2021: The Physical Science Basis" (Forster et al. 2021). The study has been cited over 400 times, earning it recognition from the prestigious *Geophysical Research Letters* journal and ranking it among the top 0.1% of papers in geosciences in the last 2 years by Web of Science.



Improved Climate Models Narrow Earth's Range of Climate Sensitivity. Equilibrium climate sensitivity (ECS) scattered against net cloud feedback for the Coupled Model Intercomparison Project 5 (CMIP5, blue) and CMIP6 (magenta) models. Asterisks indicate across-model correlations that are statistically significant at 95% confidence. Overlain shading indicates the very likely (90%) and likely (66%) confidence intervals of total cloud feedback and ECS. [Courtesy Lawrence Livermore National Laboratory; for more information, see Zelinka et al. 2020. "Causes of Higher Climate Sensitivity in CMIP6 Models," *Geophysical Research Letters* **47**(1), e2019GL085782.]

Continued from p. 75

which is a major investment that other national centers cannot easily attempt. However, a couple of respondents stated that DOE exascale computing is not yet fully realized in E3SM development.

With respect to AI/ML, DOE led a large workshop in 2021 and has the potential to lead especially in applications to climate modeling and integrating observations and models (ai4esp.org/workshop). Despite this potential and the presence of U.S.-based AI/ML experts, several respondents noted opportunities for strengthening these enabling capabilities, including (1) better integrating these efforts into BER climate science, (2) establishing more leadership, and (3) better tailoring some aspects of DOE funding to support "blue sky" research and innovation at national laboratories in a manner that is designed to further the well-defined long-term capabilities that DOE already supports.

Respondents identified data assimilation as a potential gap in DOE capabilities because it is critical to achieving a digital twinning of Earth, or the creation of a dynamic digital replica that accurately mimics the near-term evolution of Earth's relevant systems from their initial state. Data assimilation, which is already used in NOAA weather forecasting and NASA predictive global modeling, offers improved initial conditions for forecasting using high-resolution ESMs and systematically confronts ESMs with observations, thereby providing a powerful tool for identifying model errors.

5.3 Collaboration

5.3.1 Domestic Collaboration

BER impacts climate science at the national level and is generally well connected to universities and other U.S. agencies via its funding mechanisms. However, many interviews with scientific experts and responses to a Request For Information noted a need for increased domestic collaboration. As one international scientist noted, if the United States combined its intellectual and computing capabilities, then no other country likely would be able to compete; however, dispersing climate science across multiple U.S. agencies with relatively weak collaboration enables many international efforts to be competitive. Another respondent noted that multiple agencies working on the same problem could be a strength, enabling independent and unique approaches to the same problem; however, this would also require a mechanism for interagency collaboration to avoid duplication of efforts. Specific areas where improved domestic collaboration may prove beneficial include:

- **Observations**. DOE leads in ground-based observations through ARM, but collaboration is needed to integrate satellite-based observations and to support a digital twin approach to high-resolution global forecasting.
- **Human Systems Data**. BER, through the Multi-Sector Dynamics program, funds research on human impacts to the Earth system, but quality data on human systems is often lacking. Collaborations with social scientists could improve data quality.
- **Modeling**. Duplicative research efforts occur across U.S. agencies, especially in Earth system modeling. Respondents stopped short of recommending a merger of all efforts but did recommend developing a concrete plan for collaboration in the near future between modeling centers to avoid duplication of expense and effort and to increase collective impact.
- **Decision-Making**. DOE funds fundamental science relevant to decision-makers, as do many other agencies. BER's maximum impact depends on effective collaboration with other federal agencies, particularly those with a mandate for developing applied models and research (e.g., U.S. Environmental Protection Agency, U.S. Geological Survey, NOAA, and the U.S. Army Corps of Engineers), to inform management decisions.

Finally, in addition to increasing collaboration across agencies, several respondents noted a need for improved integration across DOE laboratories and between national laboratories and university teams.

5.3.2 International Collaboration

Respondents view international collaboration and leadership as a key measure of success. BER's leading

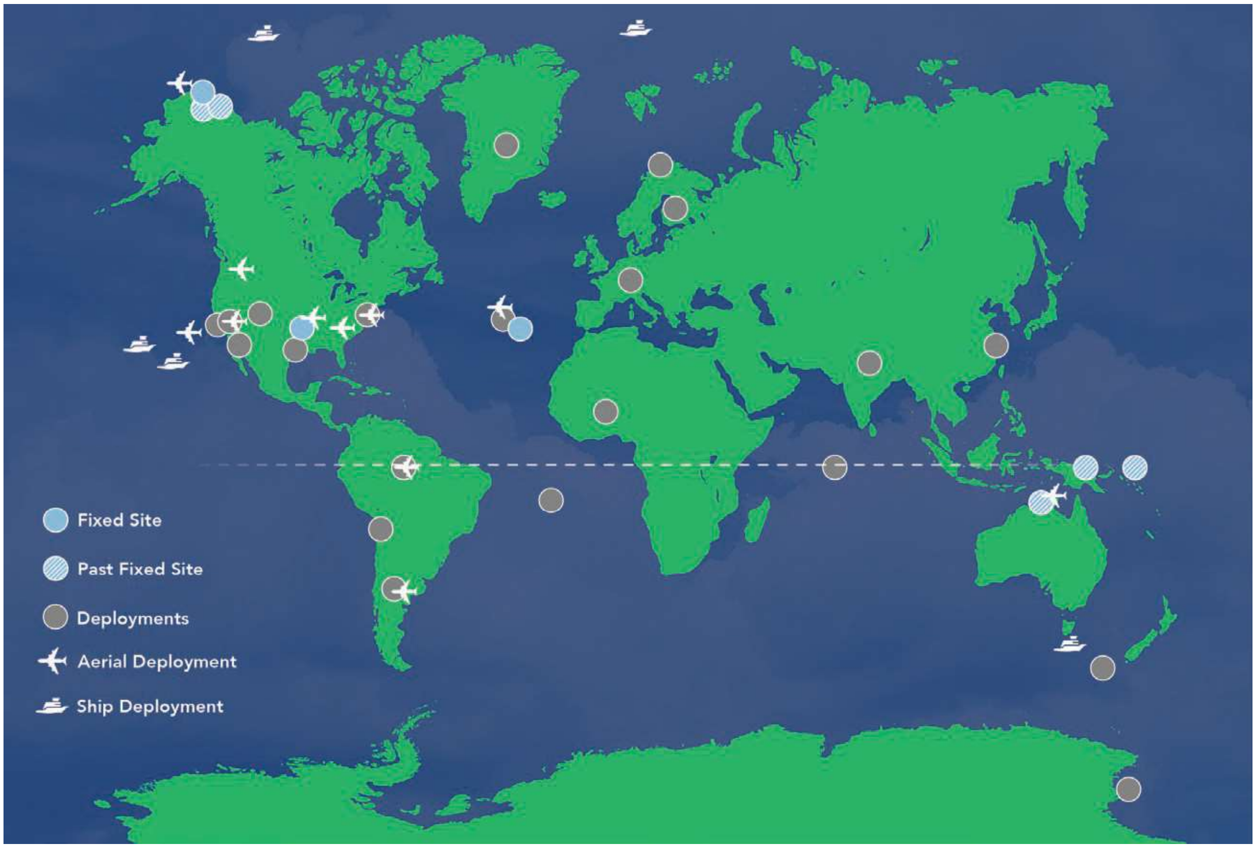


Fig. 5.5. The Global Reach of DOE's Atmospheric Radiation Measurement (ARM) User Facility. ARM fixed sites and mobile facility deployment locations have spanned all continents, simultaneously relying on and furthering a legacy of international collaboration in climate science and observations. [Courtesy ARM]

roles in IPCC assessments and on science-defining boards, such as the WCRP's, are landmarks in this regard (see Section 5. 1, p. 65).

BER leads internationally in ground-based observations, notably through the ARM program, which excels at the intersection of ground-based measurements and field campaigns (see Fig. 5.5, this page). ARM facilities are in high demand, and the international community often adds its own funding support and participation to ARM-initiated efforts (see Ch. 8: Strategies for People, Partnerships, and Productivity, p. 122). BER could improve international collaboration in this area by supporting the international community's efforts to integrate ground-based climate-observing system datasets.

In terms of Earth system modeling, BER leads internationally in integrating human-Earth system modeling. Respondents suggested that BER consider re-engaging in an integrated assessment modeling consortium, strategically develop its World Bank partnership, and partner with relevant collaborative projects funded by the European Union. BER leads in high-resolution climate modeling at the national level and stands among the leading centers at the international level thanks to extensive computational resources. International collaboration could build on shared computing resources.

BER has a legacy of international leadership in model intercomparison efforts (see Section 5.2.4, p. 72) and now partners with WCRP in the recently instituted

CMIP Project Office in the United Kingdom. The United States (but not yet BER) leads in applying AI/ML methods in modeling. Despite its excellence in process understanding (e.g., aerosol and cloud physics), BER does not yet lead in laboratory studies, which are a third pillar of climate science alongside observations and modeling. A renewed researcher exchange program could enable better integration with other international leaders, providing opportunities for BER-supported researchers to spend time at outstanding partner institutions worldwide and vice versa.

5.4 Future Opportunities

The BERAC subcommittee evaluated BER's international leadership status in climate science based on the program's roles in major international science committees, its contributions to the IPCC assessment process, and its national and international influence on climate research and similar programs.

For IPCC assessment reports, BER-supported research has contributed significantly. In terms of climate science contributions, feedback received from interviews and responses to the Request For Information indicated that BER leads internationally in many research areas. These areas include: (1) climate analyses encompassing cloud feedbacks, climate sensitivity, and attribution and detection of climate change; (2) process understanding of aerosols and clouds and their interactions; (3) Earth system modeling coupled with human-Earth system modeling; (4) global ground-based observations and associated field campaigns; and (5) climate model intercomparisons, including CMIP, the most influential and high-profile model intercomparison activity.

Continued strong support for these established international leadership areas is crucial to BER maintaining its capacities to lead. In addition, opportunities for increased leadership are outlined below in the following topical areas: high-resolution Earth system modeling, coupled human-Earth system modeling, ARM and ASR, international model intercomparisons and climate analysis, and funding modalities.

5.4.1 High-Resolution Earth System Modeling

BER uses high-performance DOE computing capabilities to perform cutting-edge research on developing a kilometer-scale ESM (see Fig. 5.6, p. 81). BER's initial success with the E3SM 3-km convection-permitting model positioned BER ahead of other U.S. contributors and among several world leaders in the field. BER also has potential to lead in the application of AI/ML approaches, particularly with respect to climate modeling and integrating observations and models. Collaboration with existing U.S. leaders and integration with interagency climate science are critical for BER to establish such leadership. Beyond AI/ML applications, BER could foster innovation in several areas by enabling small-group and principal investigator–driven research in higher-risk and higher-payoff areas. Given DOE's unique strength in computing, BER should continue to pursue high-resolution modeling efforts, ideally in collaboration with other U.S. modeling centers to avoid duplicative efforts and maximize scientific advances. Considering limited resources, BER may want to focus on developing the kilometer-scale E3SM model because the higher resolution encourages improved interagency collaboration around satellite remote-sensing data (with NOAA and NASA), which could become crucial if a digital twin approach is pursued (see Ch. 7: Integrative Science, p. 103).

5.4.2 Coupled Human-Earth System Modeling

BER is perceived as a natural home for developing capabilities in crosscutting research encompassing energy-related studies and human-Earth system modeling. Whereas BER historically led the field, European groups have recently caught up or surpassed U.S. capabilities. Politics may have negatively impacted U.S. ability to maintain consistent leadership in the field internationally. A plan to transition research-grade human-ESM forecast models to deliver operational products to public and private stakeholders, similar to weather and seasonal forecasts, could help offset politicization, as discussed further in Ch. 7: Integrative Science, p. 103. BER has the potential to lead internationally in providing decision-relevant insights

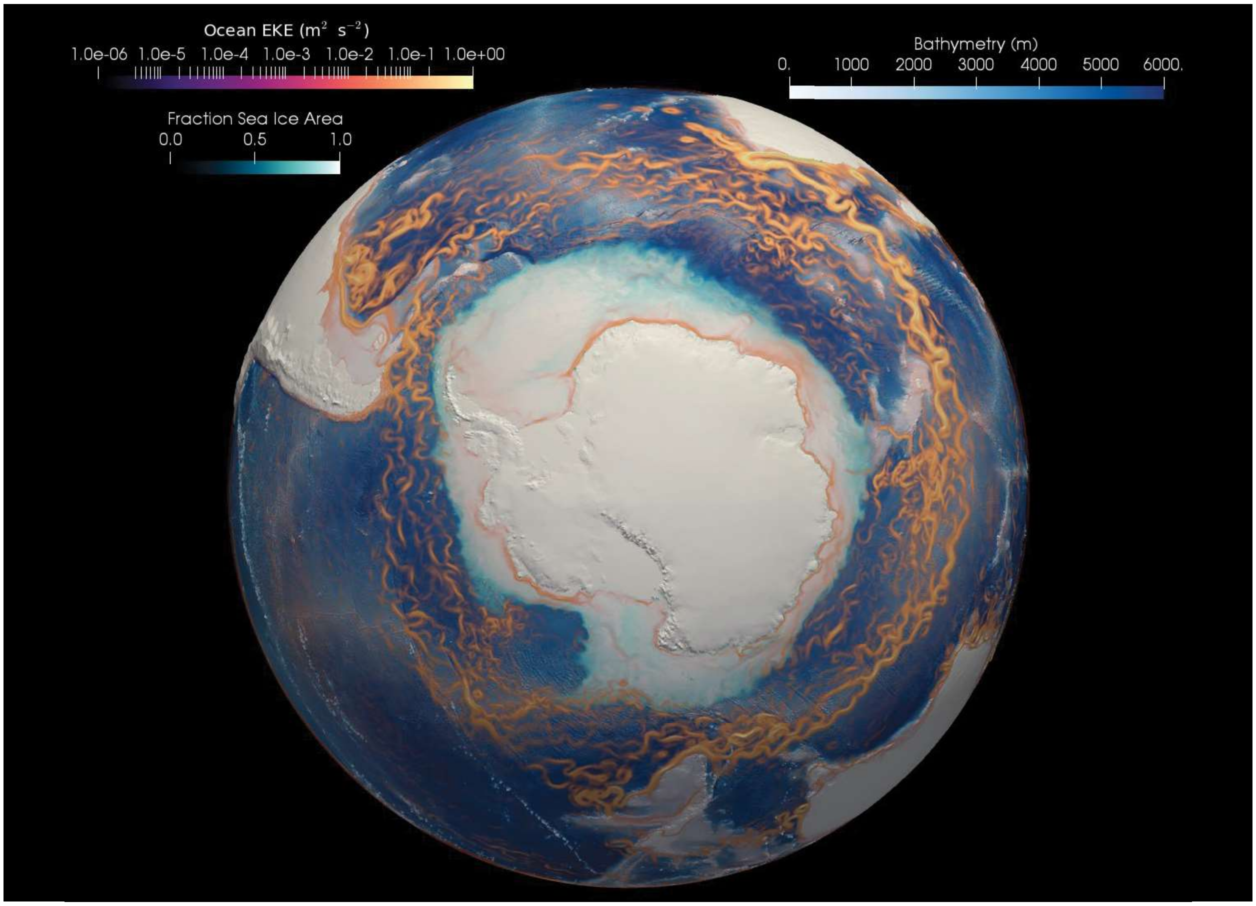


Fig. 5.6. Modeling Earth Systems in High Resolution. The Energy Exascale Earth System Model (E3SM) uses exascale computing to carry out high-resolution Earth system modeling of natural, managed, and man-made systems to answer pressing problems in DOE mission areas. This image from a high-resolution E3SM simulation shows sea-ice extent (bluish-white) around Antarctica (center) and oceanic currents associated with strong mesoscale eddy activity (orange). These currents play an important role in transporting heat from warmer mid-latitudes to Antarctica, where it can melt ice shelves. [Courtesy Los Alamos National Laboratory]

considering model uncertainties by improving predictive understanding of the coupled human-Earth system.

5.4.3 ARM and ASR

The combination of BER's ground-based measurement capabilities and field campaign support sets world standards, but the European community has now integrated a wide array of previously unaffiliated ground sites and lifted standards in some operational respects. Going forward, domestic and international ground site networks should adopt shared data quality standards and collectively deposit their historical and future data into shared databases. A stronger strategic plan could also better integrate ARM observations with ESM development, perhaps spanning E3SM and the U.S. Earth system modeling community within the context of a nationally integrated effort (see Ch. 7: Integrative Science). Finally, BER could consider establishing a major laboratory chamber user facility for cloud and aerosol research in the United States, on a par with modern European facilities. DOE laboratories offer the most appropriate environment and already house the greatest concentration of relevant expertise domestically. A history of international exchange opens the possibility of BER drawing upon existing European designs and lessons learned.

5.4.4 International Model Intercomparisons and Climate Analysis

A key aspect of BER's international leadership is its role in leading and participating in model intercomparisons such as CMIP. BER also leads in cloud feedback and climate sensitivity research, according to WCRP reports and IPCC assessment reports. BER is encouraged to continue to work through PCMDI to conduct international model intercomparison activities involving both future CMIP phases and intercomparisons organized by individual research communities. DOE's support of ESGF for CMIP data distribution and the Coordinated Model Evaluation Capabilities metrics package, which includes PMP, is critical to maintain BER leadership in multimodel diagnostics and evaluation, areas where BER could be outmoded by the European-based Earth System Model Evaluation Tool. Continuous support for cloud feedback and climate analysis research is also required to ensure BER's scientific leadership.

5.4.5 Funding Modalities

BER advances its mission areas via support for user facilities, Science Focus Areas at DOE national laboratories, and grants to domestic and international research entities external to DOE. The SFA process supports development of long-term capabilities while retaining flexibility to adjust course, but it lacks emphasis on discovery research at a small scale within laboratories. Adding a small-scale proposal-driven funding modality would provide two key advantages. First, it would allow scientists an additional avenue to participate in career-defining work of their own design, which is the norm within the wider research community, thus increasing engagement and reward. Second, seeding a diversity of high-risk, high-return ideas increases innovation. For example, the operation of discovery or blue sky grants within climate science could accelerate AI/ML applications. Another shortfall of the SFA process is the barrier it presents to funded collaboration between BER researchers and external entities. This prevents the efficient importation of expertise to fill knowledge gaps or share lessons learned. Within ESM development, collaborative engagement can accelerate learning and prevent shortfalls of model performance where expertise may be lacking. Other U.S. agencies experience similar barriers for similar reasons. BERAC recommends addressing this problem more boldly in the field of climate science and establishing sustained, substantial funding streams to support expanded collaboration with U.S. agencies and universities to improve research outcomes and ensure integration of efforts to meet societal needs.